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Evaluation of different infiltration models under long term conservation agricultural practices

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ABSTRACT

A study was undertaken to evaluate the long term effect of different conservation agriculture (CA) practices on infiltration characteristics of soil and empirical Kostiakov model and physical process based Green and Ampt, and Philip models were used to predict infiltration rates. The performance of different models was evaluated using statistical criteria. Six treatments were selected, viz. conventional tillage (CT), permanent narrow bed (PNB), permanent narrow bed with residue (PNB+R), permanent broad bed (PBB), permanent broad bed with residue (PBB+R) and zero tillage (ZT). Results showed that the initial infiltration rate was highest (22.93 cm hr^{-1}) in PBB+R and was lowest (7.64 cm hr^{-1}) in CT. Cumulative infiltration of all the treatments followed the order: PBB+R>PNB+R>PBB>PNB>ZT>CT. The 'a' values of Kostiakov model was 197.5 and 310 % higher in PBB and PBB+R as compared to CT. Steady state infiltration (ic) of Green and Ampt model was found to be highest (8.47 cm hr^{-1}) in PBB+R and was lowest (1.88 cm hr^{-1}) in CT. Sorptivity (S) parameter (cm $hr^{-0.5}$) of the Phillip model was found to be highest in PNB+R (67.33) followed by PBB+R (43.61) and lowest in CT (16.23). Highest saturated hydraulic conductivity ('K') value of Phillip model was obtained in PBB+R followed by PBB> PNB>PNB+R>CT. After checking the model performance, it has been found that simple empirical Kostiakov (1932) infiltration model represented the infiltration rate and time relationship in a better way and characterized the best fit with the experimentally observed field infiltration data.

Key words: Conservation agriculture; Infiltration; Kostiakov model; Green and Ampt model; Philip model

Farmers are usually well familiar to conventionally till the soil as it churns the soil by repeated tilling, harrowing, discing and other inter-cultural operations (Indoria *et al.* 2017). Conventional tillage operations help in seedbed preparation, weed control and speed up the organic matter decomposition and plant nutrient mineralization. But at the same time, conventional agricultural practices increase soil compaction, soil erosion, salinization and decrease soil organic matter and nutrient content (FAO 2001) and greenhouse gas emission. To overcome these problems, conservation agriculture (CA) has been considered a solution worldwide. CA is based on the principles of minimal soil disturbance; permanent soil covers with crop residues or growing cover crops, and diversified crop rotations.The advantages and challenges of CA practices have been extensively discussed (Shafeeq *et al.* 2020; Aggarwal *et al.* 2017, Chakrabarti *et al.* 2014, Pramanik *et al.* 2019 and Hobbs 2007). Immediate effects of CA are increased water infiltration (Rai *et al.* 2018) and soil moisture content (Pathak *et al.* 2017 and Bhattacharya *et al.* 2000), reduced water runoff, evaporation and soil erosion. Long term effects of CA are increases in soil organic matter, improved soil structure (Bhattacharyya *et al.* 2013), reduced weed problems and increased soil biological activity (Derpsch 1999; Hamblin 1987; Sayre 1998).

Many researchers throughout the world have shown that CA influences infiltration severely. Infiltration has been defined as the entry of water from the surface into the soil. It is widely applicable for measuring runoff loss, effective rainfall, groundwater recharge, designing of channels for soil and water conservation. Many scientists proposed different models of infiltration, viz. Green-Ampt model (1911), Kostiakov (1932), Horton (1938), Phillips (1957), Smith and Parlange model (1978) and Singh and Yu (1990). The selection of the infiltration model depends on the types of soil and field conditions. Among the above-mentioned models Green-Ampt model (1911), Kostiakov (1932), Horton (1938) and Phillips (1957) are commonly used due to its simplicity and ease of computation, out of

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which Kostiakov and Horton models are empirically derived and Phillips and Green-Ampt models are physical process based. Though several studies are available on the evaluation of different physical and empirical models of infiltration under different situations, the long term effect of different CA practices on infiltration characteristics of soil and the performance evaluation of different infiltration models are limited. Hence, a study was undertaken to evaluate the performance of different infiltration model under long term CA practices.

MATERIALS AND METHODS

The experiment was conducted in the research farm of the Indian Agricultural Research Institute (IARI). Six treatments namely, conventional tillage (CT), permanent narrow bed (PNB), PNB with residue retention (PNB+R), permanent broad bed (PBB), PBB with residue retention (PBB+R) and Zero tillage (ZT). Infiltration readings were recorded after the harvest of maize crop in the maize-wheat cropping system. Forty percent (40%) of wheat straw yield (i.e 2.6 t/ha) in PNB+R and PBB+R and for the residue removal plot, wheat crops were harvested manually and about 4.5% of wheat straw was kept as stubble in CT and ZT. A common fertilizer dose of 120 kg N, 60 kg P_2O_5 and 40 kg K_2O per ha was applied. Six irrigations were applied to the maize crop. The infiltration was measured by using Double Ring Infiltrometer. The instrument consists of two different diameters cylinders, the smaller diameter (20 cm) ring was kept inside the larger diameter (30 cm) cylinder. The volume rate of flow of water through the inner cylinder was taken, which helps to minimize the seepage loss. One empirical model of infiltration, i.e Kostiakov model and two physical process based, i.e Green Ampt model and Philips models were evaluated. Different model parameters were estimated by linear and nonlinear regression analysis in MS- excel.

A brief description of the infiltration models used in this study is as follows.

Empirical Model

Kostiakov model: Kostiakov (1932) proposed an equation to calculate cumulative infiltration

$$I = at^{-b}$$

$$i = at^{-(b+1)}$$

where, I = Cumulative infiltration (cm), i = Infiltration rate (cm hr^{-1}), t = Time (hr), a and b are constants with a > 0 and 0 < b < 1.

The parameters in the Kostiakov model were determined by plotting the infiltration rate (i) versus time (t). The slope of the curve was b and the intercept on Y-axis was a.

Physical Process-based Model

Green-Ampt Model:

$$i = i_c + \frac{B}{I}$$

where, i = Infiltration rate of soil (cm hr^{-1}), i_c=Steady state infiltration rate (cm hr^{-1}), B= constant.

Philip model: Philip (1957) proposed an infinite series solution of Richard's equation to drive a relationship between cumulative infiltration and soil properties and represented as

$$I = St^{0.5} + Kt$$

where, I = Cumulative infiltration (cm), i_o= Initial infiltration rate (cm hr^{-1}), t = Time (hr), S = Sorptivity of soil, K = Saturated hydraulic conductivity (cm hr^{-1}).

The infiltration rate was plotted against reciprocal square root of time. The slope of the best-fitted curve represented the value of K and the intercept gives the value of S/2.

The model performance was tested by computing the coefficient of determination (R^2), root mean squared error (RMSE), average relative error (AvRE) and mean absolute error (MAE).

Mean Absolute Error (MAE)

MAE is the average absolute difference between predicted and the observed value of data. It is computed as

$$MAE = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n}$$

where, x_i = Observed data values, y_i = Estimated (computed) data values.

Root mean square error (RMSE)

Root mean-squared error is the square root of mean-squared-error. This method exaggerates the estimated error—the difference between the estimated value and observed value (actual value). The root means squared error (RMSE) is computed as:

$$RMSE = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(x-y)^2\right)}$$

Average Relative Error (AvRE)

The average relative error (AvRE) was calculated using the following equation (Zhou *et al*. 2007a,b):

$$AvRE = \left[\frac{1}{N}\sum_{i=1}^{n}\left(\frac{P_i - O_i}{O_i}\right)*100\right]$$

The higher value of r^2 and lower values of RMSE, MAE and AvRE indicates better fitting of the model.

RESULTS AND DISCUSSION

Effects of different CA practices on infiltration characteristics

The initial infiltration rate was highest (22.93 cm hr^{-1}) in PBB+R and was lowest (7.64 cm hr^{-1}) in CT (Table 1). The initial infiltration rates of PNB, PNB+R, PBB and ZT were 15.29 cm hr^{-1}, 20.37 cm hr^{-1}, 17.20 cm hr^{-1} and 11.46 cm hr^{-1}, respectively (Table 1). The steady state infiltration rate was highest (7.49 cm hr^{-1}) in PBB+R and the time taken to reach was 2.58 hr. The lowest steady state infiltration rate of 2.11

Table 1 Characteristics of infiltration of soil under different CA treaments

Treatment	Initial infiltration rate (cm hr^{-1})	Steady state infiltration rate (cm hr^{-1})	Time to reach steady state (hr)	Cumulative infiltration (cm)
CT	7.64	2.11	1.62	5.00
PNB	15.29	4.78	1.17	20.61
PNB+R	20.37	5.12	2.33	22.64
PBB	17.20	6.02	1.50	13.79
PBB+R	22.93	7.49	2.58	27.17
ZT	11.46	3.50	2.17	11.15

cm hr^{-1} was observed in CT plot and time taken to reach was 1.62 hr. The result showed that in all the residue applied plots initial infiltration rate and steady state infiltration rates were higher. Cumulative infiltration of all the treatments followed the order: PBB+R>PNB+R>PBB>PNB>ZT>CT. Several researchers have reported that better soil structure and soil pore connectivity enable higher infiltration and eventually better available water for crop production (Aggarwal *et al.* 2017; Shaxson 2003; Thierfelder *et al.* 2005) in different CA practices. From a two years study from Zambia and Zimbabwe, Thierfelder and Wall (2009) reported that infiltration was greater on residue protected undisturbed soils than on conventionally tilled and unprotected soils.

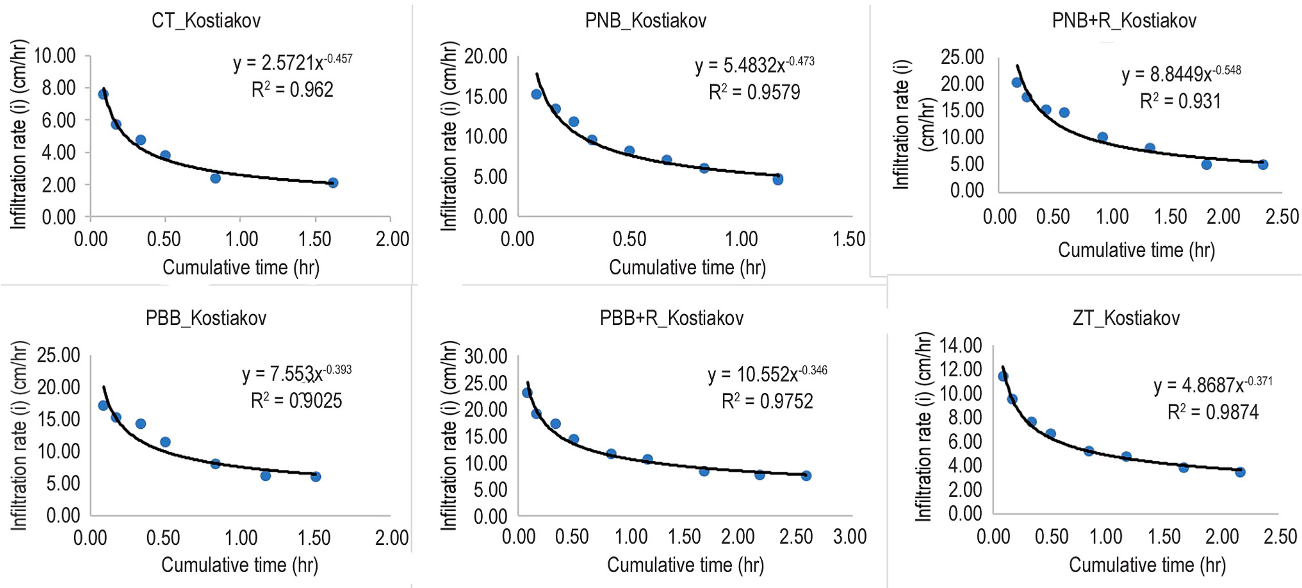

Fig 1 Infiltration rate (i) vs cumulative time (t) for Kostiakov model

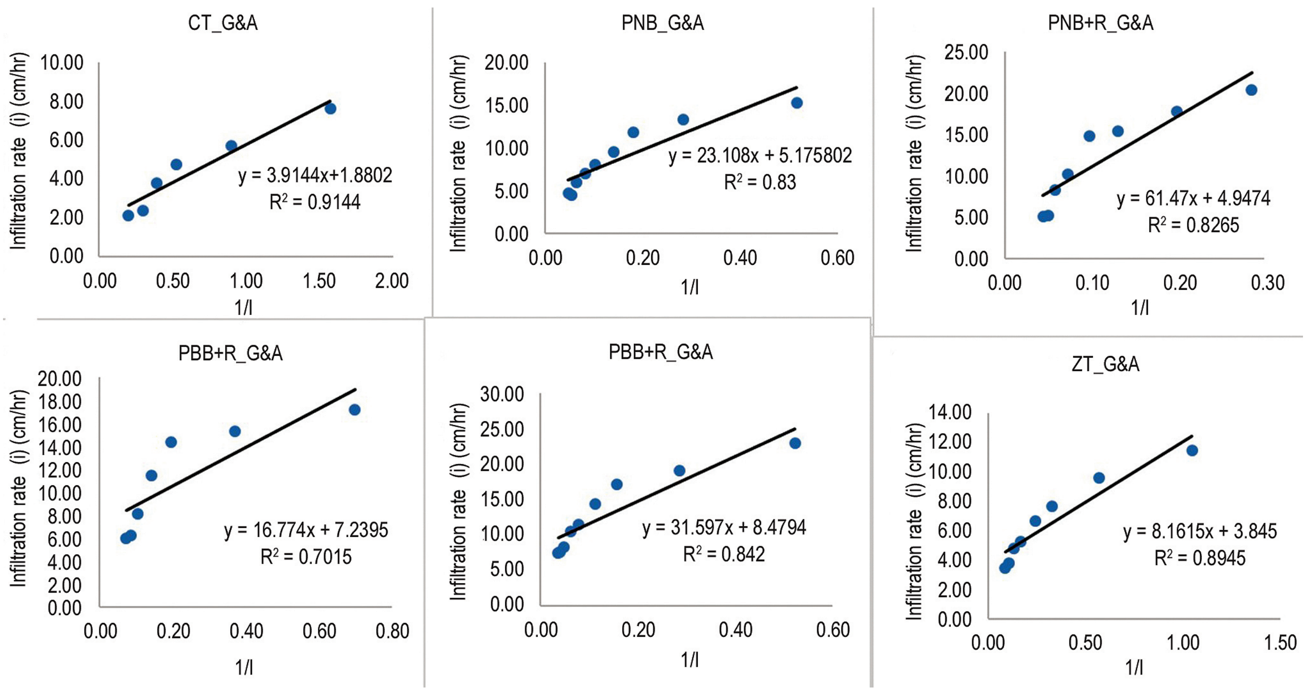

Fig 2 Infiltration rate (i) vs 1/ Cumulative Infiltration (I) for Green and Ampt model.

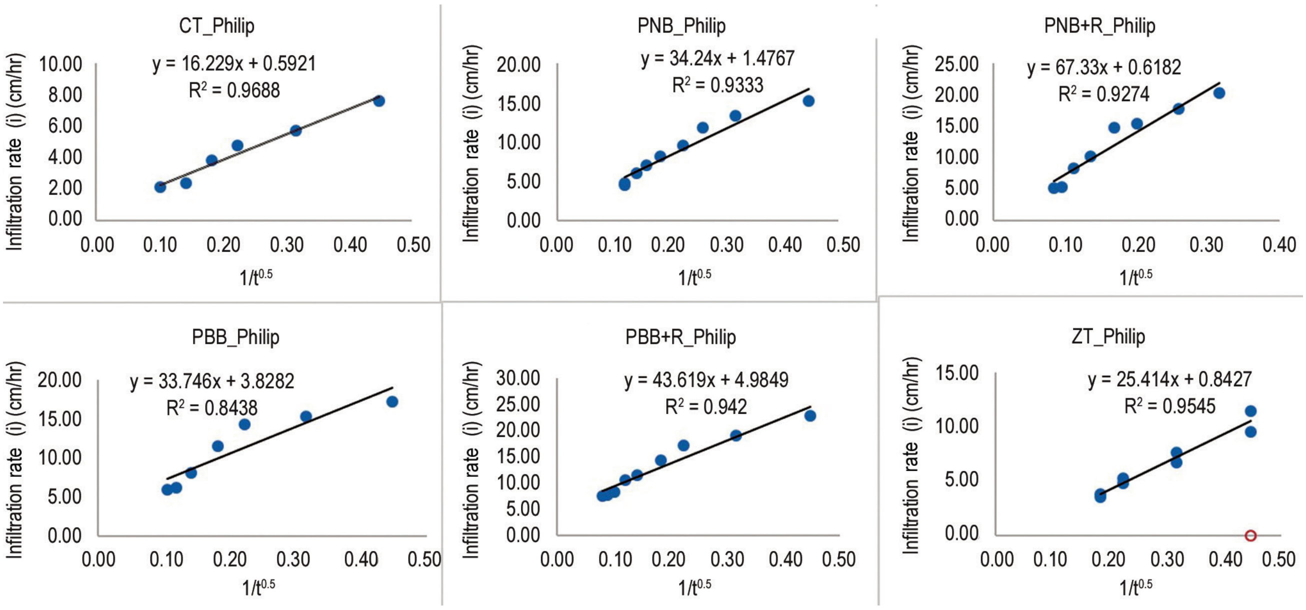

Fig 3 Infiltration rate (i) vs 1/t 0.5 for Philip model.

Effects of different CA treatments on selected infiltration model parameters

The model parameters for Kostiakov, Green Ampt and Philip models were estimated by fitting the observed infiltration data (Table 2).The 'a' parameter in Kostiakov model signifies the initial infiltration rates. The estimated 'a' value was highest in PBB+R, followed by PNB+R and lowest value was obtained in CT (Table 2 and Fig 1). The 'a' values was 197.5 and 310 % higher in PBB and PBB+R as compared to CT. The observed initial infiltration rate also follows the same trend. The negative sign of 'b' parameter in Kostiakov model indicated the rate of reduction in filtration with time. The lowest 'b' value (-0.346) in PBB+R indicates that the infiltration phenomena is prolonged which might be due to the more porous environment. The higher values of 'b' of -0.457, -0.473 and -0.548 in CT, PNB and PNB+R, respectively, indicates that steady state infiltration is obtained in shorter period. In Green and Ampt model, i_c is the steady state infiltration which was found to be highest (8.47 cmhr^{-1}) in PBB+R and was lowest (1.88 cm hr^{-1}) in CT (Table 2 and Fig 2). The model estimated i_c values followed the order: PBB+R>PBB>PNB>PNB+R>ZT>CT. The model underestimated the steady state infiltration rate for CT and PNB+R. Steady state infiltration rates were overestimated for all other treatments. Likewise, 'B' parameter (cm^2 hr-1) in Green Ampt model, which is dependent on initial infiltration rate was lowest in CT (3.9) (Table 2 and Fig 2). These results are in line with experimentally measured value. Sorptivity (S) parameter (cm hr$^{-0.5}$) of Phillip model is related to initial soil water content and porous environment of the CT (16.22) (Table 2 and Fig 3). Higher value of 'S' in residue applied plots was due to more porous environment and better soil structure than other treatments (Rai *et al.* 2018).'K' value of Phillip model is saturated hydraulic conductivity. Highest values of 'K' was obtained in PBB+R followed by PBB> PNB>PNB+R>CT which are almost similar to the experimentally observed values (data not sown). Model estimated 'K' value for ZT was found to be negative which indicated some unexplained error caused due to poor curve fitting of the model.

Table 3 Evaluation of infiltration models under different conservation agriculture

Treatment	R^2	RMSE	MAE	AvRE
Kostiakov model				
CT	0.96	0.33	0.96	0.43
PNB	0.95	1	0.72	0.33
PNB+R	0.93	3.16	2.72	21.93
PBB	0.9	1.64	1.2	0.79
PBB+R	0.97	1	0.78	0.19
ZT	0.98	0.34	0.27	0.1
Green and Ampt model				
CT	0.91	0.56	0.53	4.32
PNB	0.83	1.49	1.30	4.86
PNB+R	0.82	2.24	1.91	7.83
PBB	0.70	2.29	2.13	6.5
PBB+R	0.84	2.07	1.81	4.06
ZT	0.89	0.85	0.76	3.3
Philip model				
CT	0.96	0.33	0.27	0.99
PNB	0.93	0.93	0.79	2.31
PNB+R	0.92	1.45	1.18	4.01
PBB	0.84	1.66	1.49	3.78
PBB+R	0.94	1.25	1.06	1.88
ZT	0.95	0.56	0.45	0.59

Table 2 Parameters and coefficients of various infiltration models obtained by least-square fitting to the infiltration data for different CA treatments.

Treatment	Kostiakov model		Green and Ampt model (1911)		Philip model	
	a (cm/hr)	*b*	i_c (cm/hr)	B (cm^2/hr)	S (cm $hr^{-1/2}$)	K (cm/hr)
CT	2.57	-0.45	1.88	3.91	16.22	0.59
PNB	5.48	-0.47	5.17	23.1	34.24	1.47
PNB+R	8.84	-0.54	4.94	61.47	67.33	0.61
PBB	7.55	-0.39	7.23	16.77	33.74	3.82
PBB+R	10.55	-0.34	8.47	31.59	43.61	4.98
ZT	4.86	-0.37	3.84	8.16	25.41	-0.84

Performance evaluation of different infiltration models

The performance evaluation of three infiltration models was done by calculating coefficients of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and average relative error (AvRE) (Table 3). Greater values of R^2 and lesser value of RMSE, MAE and ARE indicate the well performanceof the model. Values of R^2varied between 70-98%, RMSE between 0.33-3.16, MAE between 0.27-2.72 and AvRE between 0.1- 21.93% in different models. From Table 3, it is clear that Kostiakov, Green Ampt and Philip models performed well for CT and five CA practices. But the negative value of 'K' obtained from the physical process based Philip model shows the poor capability of statistical techniques in determining model coefficients. Similar inconsistencies in obtaining the model coefficients have been reported by previous workers (Rai *et al.* 2018; Shukla *et al.* 2003; Kannan *et al.* 2010).

Conclusion

The findings of the current study are useful to understand the process of infiltration phenomena and to predict the infiltration rates under CT and different CA practices. The initial infiltration rate, steady state infiltration and cumulative infiltration were highest in the PBB+R plot. The time required to reach steady-state infiltration was also highest in PBB+R which shows that long term adoption of CA practices could improve the soil structure and distribution of soil water in the profile is also good. After checking the model performance, it has been found that simple empirical Kostiakov (1932) infiltration model represented the infiltration rate and time relationship in a better way and characterized the best fit with the experimentally observed field infiltration data.

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